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Fault displacements, damage zones, and associated fracturing in geothermal reservoirs

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Active faults commonly have great effects on the transport of crustal fluids, such as geothermal water. During fault slip all the pores and small fractures that meet with the slip plane become interconnected so that the inner part of the fault, the fault core, consisting of breccia or gouge, may suddenly develop a very high hydraulic conductivity. The best evidence of palaeo-geothermal fluid transport, for example in deeply eroded, inactive fault zones, are networks of mineral veins. Inactive faults, however, may have low permeabilities and even act as seals, particularly if they develop clay smear along their planes. In natural and man-made geothermal reservoirs, the orientation of fault zones in relation to the current stress field and their internal architecture needs be known as accurately as possible. One reason is that the activity of the fault zone depends on its angle to the principal stress directions. Another reason is that the outer part of a fault zone, the damage zone, comprises numerous fractures of various sizes. The majority of these fractures is oriented subparallel to the main fault plane, in which case the current stress field may also have strong effects on the permeability of the fault damage zone. When the maximum principal compressive stress is at a high angle to the fault strike, many fractures in the damage zone tend to close and fluid transport is reduced. When, however, the maximum principal compressive makes a small angle with the fault strike, fractures in the damage zone tend to be open and fluid transport is enhanced. Commonly there is a correlation between the trace length of a fault, the fault displacement, and the damage zone thickness, so that these correlations may be used for predicting of fault parameters in reservoirs. In mechanically layered host rocks, however, where the stiffnesses of the rocks (their Young's moduli) change between layers, this correlation is less clear.

Here we present field examples of faults, and associated joints and mineral veins, in palaeogeothermal fields, and potential host rocks for man-made geothermal reservoirs, respectively. We studied several localities of different lithologies and tectonic settings: (1) sandstone and shale layers of the Buntsandstein (Lower Triassic) in Bad Karlshafen, Northern Germany with oblique-slip normal faults; (2) limestone and shale layers of the Blue Lias Formation (Lower Jurassic) near Kilve, Somerset Coast (Southwest England) with (mainly) normal faults; (3) equivalent lithologies as in (2) at Nash Point, Glamorgan Coast (South Wales) with strike-slip faults; (4) siltstone layers of the Mercia Mudstone Group (Upper Triassic) at Watchet, Somerset Coast, with partly inverted normal faults; and (5) basaltic lava flows (Upper Tertiary) at the Husavik-Flatey Fault, a major structure of the Tjörnes Fracture Zone, a transform fault in North Iceland. (1) is an outcrop analogue of a fractured geothermal reservoir horizon in the North German Basin, (2-5) represent palaeogeothermal fields with mineral veins of calcite (2,3), gypsum (4), or quartz, chalcedony and zeolites (5).

The field studies in the Buntsandstein (1) show that the fault normal displacements correlate with the fault heights (dip dimensions). The normal displacement along these faults, however, not only increases towards the centres of the faults, but also depends on the mechanical properties of the host rocks. In soft (low Young's modulus) shale layers, the normal displacement is always larger than in stiffer (higher Young's modulus) sandstone layers. The joint frequency increases towards the fault zones. In the study areas of palaeogeothermal fields (2-5), all the mineral veins are clearly related to the faults and occur almost exclusively in the damage zones, indicating that geothermal water was transported along the then-active faults into the host rocks. In the Husavik-Flatey-Fault (5), the mineral veins were generated at the time when the damage zone supplied fluids to surface geothermal fields. Field measurements indicate that in all the localities, about 80% of the fractures in the fault damage zones are extension fractures, and only 20% are shear fractures. In the Blue Lias areas (2,3) there is evidence that the veins were injected as hydrofractures (fractures generated by internal fluid overpressure) from the fault planes into the limestone layers.

To understand the development of fault zones in geothermal reservoirs we have run numerical models using the finite-element and boundary element methods. One series of models focuses on the displacements of normal and strike-slip faults depending on the mechanical properties (particularly Young's moduli) of the layered host rocks and the damage zones. These models show that the displacements of the faults vary positively with the thicknesses of the damage zones. The models also show that in soft host rock layers, the fault displacement is larger than in stiff layers. The second series of models focuses on hydrofracture injection from fault planes into the fault damage zone. We explore different injection angles, hydrofracture overpressures, and stress field orientations.

Our studies contribute to understanding fluid transport in future man-made geothermal reservoirs. In most geothermal reservoirs, fluid flow is largely controlled by the permeability of its fracture network. In order to generate permeability in man-made reservoirs, interconnected fracture systems, needed for significant permeability, are formed either by creating hydraulic fractures or by massive hydraulic stimulation of the existing fracture system in the host rock. For effective stimulation, the geometry of the fracture system and the mechanical properties of the host rock must be known. Studies of fracture systems in exposed paleogeothermal fields can help understand the permeability development in stimulated reservoirs.